

Multi-temporal self-organizations in 1,3-*O,O'*-bis(dodecyl)calix[4]arene†Alexander D. Q. Li,^{*a} Manuel Marquez^b and Mingming Guo^a^a Department of Chemistry and Center for Materials Research Center, Washington State University, Pullman, WA 99164, USA. E-mail: dequan@wsu.edu; Fax: +1 509-335-8867; Tel: +1 509-3357196^b Kraft Foods, 801 Waukegan Road, Glenview, IL 60025, USA. E-mail: mmarquez@kraft.com; Fax: +1 847-646-7302; Tel: +1 847-646-3357

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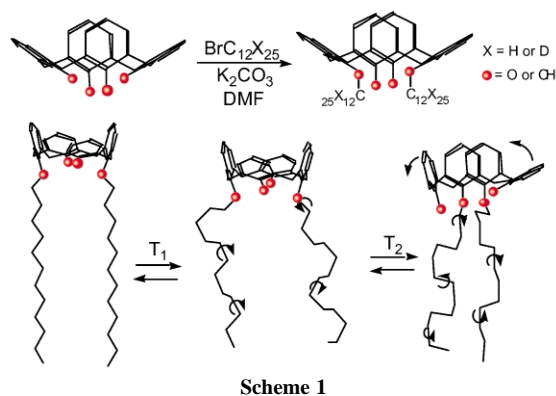
After heat erases the order in 1,3-*O,O'*-bis(dodecyl)calix[4]arene, it self-organizes the phenyl units into a rigid calix bowl first at $T_2 = 111$ °C, followed by the formation of all-*trans* alkyl chains at $T_1 = 62$ °C, which eventually yields a stable cone-shaped structure at room temperature.

As a bundle of tethered single aromatic molecules in a ring structure, calixarene can be viewed as a nanoscale molecular object with each individual unit pivoting upon the bridging methylene groups. As a result, cone, partial cone, 1,2-alternate, and 1,3-alternate configurations are interchangeable. Such molecular mechanics can be exploited to construct chemical sensors,¹ triggering mechanisms for inclusion,² and self-organized 'smart' systems.³ In this report, we present a series of self-organization events in 1,3-*O,O'*-bis(dodecyl)calix[4]arene, which leads it from a random structure to an ordered cone-shaped calixarene nano-object.

Synthesis of 1,3-*O,O'*-bis(dodecyl)calix[4]arene were conveniently carried out by reacting calix[4]arene with a 4 times excess of 1-bromododecane or deuterated 1-bromododecane in the presence of K_2CO_3 in DMF.⁴ Typical reactions were run for 18 h at 95 °C (Scheme 1); the pure product was obtained by extracting the mixture in water with methylene chloride, followed by crystallization with the addition of ethanol.⁵ ¹H NMR shows, interestingly, that there are only two dodecyl chains incorporated into the *trans*-1,3-positions of the calix[4]arenes. To synthesize fully substituted *O,O',O'',O'''*-tetraakis(dodecyl)calix[4]arene, one must use a stronger base such as sodium hydroxide in DMF. Despite that, two unsubstituted phenol units are still small enough to be fluxional, which could have yielded partial cone or 1,3-alternate structures, 1,3-*O,O'*-bis(dodecyl)calix[4]arene and its deuterated derivative adopt a stable cone configuration as indicated by a set of characteristic doublets from bridging methylene proton resonance at 4.30 ppm (axial proton) and 3.35 ppm (equatorial proton) with typical coupling, $J = 13$ Hz. The structure of calixarene and its deuterated derivative was also confirmed with MALDI mass

spectrometry. The molecular weight peak appeared at $M = 760.5$ (exact mass) and parent mass plus one sodium ion appeared at $M + Na^+ = 783.5$ for calixarene with protonated chains. For the calixarene with deuterated chains, we observed a mass corresponding to the complex between calixarene and a sodium ion at $M + Na^+ = 833.3$. This is not surprising because the pocket of calix[4]arene formed by the phenol oxygen atoms is ideal for inclusion of the smaller alkaline metal ions such as sodium, and sodium is ubiquitous in MALDI experiments.

Differential scanning calorimetry (DSC) showed 1,3-*O,O'*-bis(dodecyl)calix[4]arene to have two exothermal peaks (Fig. 1), indicating two order-to-disorder transitions. The low-temperature (T_1) peak corresponds to the side chain order-to-disorder transition, whereas the high-temperature transition peak (T_2) at 110 °C corresponds to the fluxional motions of the arene units. Heating the sample to 250 °C destroyed all orders or erased the memory in the system and produced an amorphous material, as indicated by the immediate DSC run (trace a in Fig. 1). The small and growing exothermic peak at 111 °C indicated that the rigid calixarene bowls just began to crystallize during the process of quenching and re-scanning. Upon standing at rt for 2 h, the system remarkably self-organized and established order for both the rigid cone configuration and all *trans*-dodecyl chains, as evidenced by the two well defined exothermal peaks at $T_1 = 62$ °C and $T_2 = 111$ °C in the DSC trace (d in Fig. 1). The appearance of the shape peak at 62 °C (c,d in Fig. 1) indicates that the alkyl chains in the sample as prepared (a in Fig. 1) have considerable disorder. Repeated cycles of heating and cooling convert *gauche* to *trans* configurations. Carefully designed DSC experiments revealed that the rigid arene units began to assemble immediately (b in Fig. 1) after quenching from 250 °C, while the flexible alkyl chains started to self-organize 0.5 h later (c in Fig. 1). This can be understood by noting that aromatic systems are rigid and more elastic and therefore self-organize first, whereas alkyl chains are soft and flexible and have slower kinetics. If the calixarene system was



Scheme 1

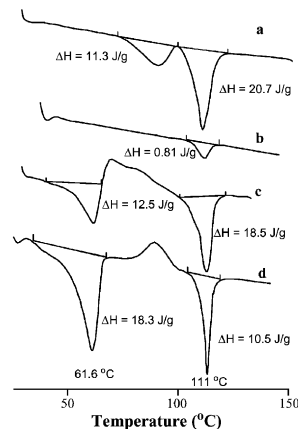


Fig. 1 Differential scanning calorimetry traces of 1,3-*O,O'*-bis(dodecyl)calix[4]arene as prepared (a), immediately after quenching from 250 °C (b), 1 h (c) and 2 h after quenching (d). The rigid cone-shaped calixarene bowl self-reorganizes first ($T_2 = 111$ °C), followed by the ordering of alkyl chains ($T_1 = 61.6$ °C).

† Electronic supplementary information (ESI) available: experimental procedure, Fig. S1: FTIR spectra, Fig. S2: solid-state CP/MAS ¹³C NMR spectra. See <http://www.rsc.org/suppdata/cc/b2/b200214k/>

annealed at 60 °C overnight, DSC results indicated that only the alkyl chains randomized, as evidenced by the disappearance of the order-to-disorder phase transition at T_1 , while the order of the rigid calixarene units was intact (T_2).

Variable temperature FTIR was employed to monitor the self-assembly processes of calixarenes after cooling from 250 °C to rt. In order to separate the rigid cone vibrational information from that of the flexible alkyl chains, we further synthesized 1,3-*O,O'*-bis(dodecyl)calix[4]arene- d_{50} with deuterated dodecyl ($C_{12}D_{25}$) chains. After the low temperature transition (rt to 90 °C), we observed a frequency shift of the symmetric C–D vibration from 2094 to 2096 cm^{-1} (Table 1), suggesting configuration changes or ‘melting’ of the flexible alkyl chains.⁶ Frequencies associated with the rigid cone structures such as aromatic (Ar) rings, bridging methylenes (Ar–CH₂–Ar), and aromatic carbon hydrogen stretching (Ar–H), remain constant, which is a sign that the rigid cone configuration was not perturbed much. This result is consistent with the DSC observation that annealing the sample at 60 °C overnight completely removes T_1 while leaving the high temperature transition peak (T_2) untouched. Above T_2 , the symmetric vibration of the methylene group linking phenyl units shifted about 4 cm^{-1} from 2852 to 2856 cm^{-1} . This is a clear indication of twisting the methylene groups upon rocking the phenyl groups back and forth. As the phenyl groups become disordered, the aromatic hydrogen stretching vibration bands change from a doublet to a triplet, with frequency shifts. The combining of two out-of-plane bending modes into one vibration band at 758 cm^{-1} , which is characteristic for 1,2,3-substituted benzene, also manifests the transition from order-to-disorder for the rigid aromatic cone structure. Furthermore, the phenyl-ring modes and the aromatic ether modes between 990–1100 cm^{-1} also sense structural changes in the rigid cone by weakening their vibrations by 2 cm^{-1} . In the phenol O–H region, we observed a broad band centered at 3333 cm^{-1} at both rt and 90 °C, indicating that there is little activity involving the phenoxy groups for the T_1 transition. The low vibration frequency of this band suggests a possible intramolecular hydrogen bond, presumably from the 2,4-hydroxy groups on the calixarene. At 120 °C, this hydroxy vibration shift to higher frequency with a pronounced component at 3500 cm^{-1} , indicates that there are more free hydroxy groups instead of the hydrogen bound hydroxy groups. This observation corroborates with the assignment of T_2 transition to the rocking of the phenyl rings.

In solid state CP/MAS ^{13}C NMR, the chemical shift of a given ^{13}C atom is influenced by the configuration changes of the γ -positions related to the observed carbon.⁷ In hydrocarbon chains, if the probability of *gauche* character is P_{gau} and the number of substitutions on the γ -carbon is n , one can derive the shielding produced by the γ -effect⁸ as, $\Delta\delta = n\gamma_{C-C}P_{\text{gau}}$, where the unit γ -*gauche* shielding effect is estimated as $\gamma_{C-C} = -5.2$ ppm. To understand the self-organization processes in the memory erase or recovery, we applied solid-state variable-

Table 1 Infrared frequency (cm^{-1}) summary of 1,3-*O,O'*-bis(dodecyl)calix[4]arene- d_{50} . The shifts of C–D bands (ν_s, ν_a) correspond the soft alkyl chains while the other bands come from the rigid calixarene bowl

Assignment	C–D: ν_s, ν_a		Ar–CH ₂ –Ar		1,2,3-sub. Ar	
rt	2094	2196	2852	2921	760	748
90 °C	2096	2196	2852	2921	758	748
120 °C	2096	2198	2856	2921	758	Sh

Assignment	Ar–H			Ar rings/C–O		
rt	Sh	3037	3058	995	1088	1099
90 °C	Sh	3037	3056	995	1088	1099
120 °C		3020	3039	993	1086	1097

temperature CP/MAS ^{13}C NMR techniques. At rt, we observed the resonance of the alkyl chains at 34 ppm corresponding to an ordered state (all *trans*, zigzag). At 90 °C ($T_1 < T < T_2$), we found that these alkyl chain resonances shifted to 32 ppm, which was equivalent to a *gauche*-conformation probability of 20%.⁹ These results suggest that about half of the total alkyl chain populations are disordered (liquid-like) above T_1 . The aromatic resonances remained sharp and constant, suggesting that phenyl rings were not fluxional. At 120 °C, the total resonance shift for the alkyl chains was $\Delta\delta = -3$ ppm, which indicated about 75% liquid-like state in alkyl chains. More importantly, the other resonances disappeared due to molecular motion or dynamics on the NMR time scale. This leads us to conclude that both the rigid calixarenes and the flexible alkyl chains are at constant flux above T_2 . The order-to-disorder transitions were observed in both 1,3-*O,O'*-bis(dodecyl)calixarene and deuterated 1,3-*O,O'*-bis(dodecyl)calixarene- d_{50} .

Both variable-temperature FTIR and solid CP/MAS ^{13}C NMR showed a hysteresis for the calixarene system to fully recover to the ordered states. Upon cooling, it frequently required longer times before the ordered states were established, but the calixarene self-organized into the original ordered state eventually, which was confirmed repeatedly by both solid state NMR, variable-temperature FTIR, and DSC.

In summary, we report two self-organization processes with different kinetics within a single calixarene system. The results demonstrate that such supramolecular systems, upon perturbation, have a ‘memory’ effect and can find pathways to direct themselves towards the ordered structure. In a system where two self-organization processes couple and compete with each other, we found that the rigid cone self-assembled first, followed by the flexible hydrocarbon chains.

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Notes and references

- Y. Kubo, S. Maeda, S. Tokita and M. Kubo, *Nature*, 1996, **382**(6591), 522–524.
- J. L. Atwood, L. J. Barbour, C. L. Raston and I. B. N. Sudria, *Angew. Chem., Int. Ed.*, 1998, **37**(7), 981–983.
- H. Bock, A. John, C. Nather and Z. Havlas, *J. Am. Chem. Soc.*, 1995, **117**(36), 9367–9368.
- C. D. Gutsche, *Acc. Chem. Res.*, 1983, **16**, 161–170.
- 1,3-*O,O'*-Bis(dodecyl)calixarene: Yield, 91%. 1H NMR ($CDCl_3$) δ (ppm) showed 1,3-bis-substitution characters. 7.03 (4H, d), 6.90 (4H, d), 6.72 (2H, t), 6.62 (2H, t), 8.17 (2H, s, Ar–OH) 4.30 (4H, d, Ar–CH₂–Ar), 3.35 ppm (4H, d, Ar–CH₂–Ar); alkyl chains (C_{12}). 3.98 (4H, t, Ar–O–CH₂–R), 2.06 (4 H, t), 1.68 (4H, t), 1.44 (16 H, t), and 0.86 (6H, t). ^{13}C NMR ($CDCl_3$ -d) δ (ppm): 153 and 151 (Ar–OR), 133 and 128 (Ar, *ortho* to OR), 127 and 126 (Ar, *meta* to OR), 122 and 121 (Ar, *para* to OR), 76.7 (CH₂–O–Ar), 31.9 (Ar–CH₂–Ar), 31.4–29.4 (Alkyl chains), 26.0 (γ' -CH₂), 22.7 (β -CH₂), 14.1 (α -CH₃). Mass spectrometry MALDI, Empirical formula: $C_{52}H_{72}O_4$, m/z (%): 783.5 (100) [$M + Na^+$], 760.5 (23) [M^+]. IR (KBr): $\nu = 3300$ (O–H), 3025–3070 (Ar–H, weak), 2922 (C–H, as), 2853 (C–H, s), 1466, 1440, 1267, 1248, 1216, 1196, 1159, 1089, 1008, 762 (1,2,3-sub–Ar), 753 (1,2,3-sub–Ar). For 1,3-*O,O'*-bis(dodecyl)calixarene- d_{50} : Yield: 81%. MALDI 833.4 (100) [$M + Na^+$].
- N. Sandhyarani, M. P. Antony, G. P. Selvam and T. Pradeep, *J. Chem. Phys.*, 2000, **113**(21), 9794–9803.
- The chemical shift of a given ^{13}C atom is influenced by the substituents in the α , β , and γ -positions related to the observed carbon. While α and β -substituents have fixed contributions to the observed chemical shift of the observed carbon, γ -substituents have a conformation origin and are useful in characterizing both the conformations and microstructure of micromolecular assembly.
- R. Born and H. W. Spiess, *Macromolecules*, 1995, **28**(23), 7785–7795.
- Quantitatively, the rotating C–C bonds are expected to have 40% *gauche* conformation, a value based on an energy difference of about 2.8 kJ mol⁻¹ between *gauche* and *trans* conformations. Accordingly, one expects a chemical shift up field of $\Delta\delta = 2(0.4)(-5.2)$ ppm = -4.16 ppm for a transition from a fully ordered, all-*trans* conformation to a completely disordered state with 40% of *gauche*.